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Comparative Evaluation of Three Shaft Seals Proposed for High Performance Turbomachinery

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COMPARATIVE EVALUATION OF THREE SHAFT SEALS PROPOSED FOR HIGH PERFORMANCE TURBOMACHINERY

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SUMMARY

Experimental pressure profiles and leak rate characteristics for three shaft seal prototype model configurations proposed for the space shuttle turbopump have been assessed in the concentric and fully eccentric, to point of rub, positions without the effects of rotation. The parallel-cylindrical configuration has moderate to good stiffness with a higher leak rate. It represents a simple concept, but for practical reasons, for example, possible increases in stability, all such seals should be conical-convergent. The three-stepdown-sequential, parallel-cylindrical seal is converging and represents good to possibly high stiffness when fluid separation occurs, with a significant decrease in leak rate. Such seals can be very effective. The three-stepdown-sequential labyrinth seal of 33-teeth (i.e., 12-11-10 teeth from inlet to exit) provides very good leak control but usually has very poor stiffness, depending on cavity design. The seal is complex and not recommended for dynamic control. While the test fluids were nitrogen and hydrogen, the use of corresponding states analogies extends their validity to most simple fluids and fluid mixtures.

INTRODUCTION

While many reports concerning the design of shaft seals for perfect gas flows (e.g., (1), (2)) have been published, very little experimental or theoretical information is available to guide the designer when the shaft seal must accommodate a real fluid over a wide range of thermodynamic states.

In designing a seal for high-performance turbomachines, the seal designer may select a cylindrical bore seal or perhaps introduce a series of Rayleigh steps into the design or elect to rely on a standard labyrinth type seal. In any case, three fundamental problems must be resolved: (i) determination of the leak rate and associated pressure signature or profile, (ii) the response of the pressure signature to eccentric positioning of the centerbody (which provides a measure of seal stiffness essential to turbomachine stability), and (iii) applicability of these results to other working fluids. Currently, these problems are resolved empirically, although much effort is being devoted toward an elementary theoretical understanding (3).

In previous work (4, 5, 6), critical mass flux or leak rates, and pressure signatures were established for flow through three simulated turbopump shaft seals, namely, cylindrical, stepped cylindrical, and labyrinth, in the concentric and fully eccentric (to point of rub) positions. The data were taken with the fluids nitrogen and hydrogen. In general the mass flux, or leak rate, for each configuration could be grouped using the principles of corresponding states and the theory of two-phase-choked flows; however, the presssure profiles were not in direct correspondence.

During the testing of the three-step cylindrical seal in the fully eccentric position, an unusual low pressure profile was observed at the 180° maximum clearance position which significantly altered seal stiffness (5). In an effort to understand this phenomenon, several experimental and theoretical programs were undertaken (7-10). The flow rate and pressure profiles for flow through the Borda and orifice type inlets* were assessed over a large range in inlet pressure and temperature for the fluids hydrogen and nitrogen. The unusual low pressure profile was identified with inlet separation and associated jetting phenomena**. The existence of this phenomenon was mapped and related to inlet pressure, temperature, length to diameter ratio (L/D), and surface roughness. Recompression of the jet could occur immediately, or somewhere within the tube, or beyond the test section length. Application of backpressure of up to 40 percent of the inlet stagnation pressure did not alter the jetting effects.

The flow rate and pressure response data for the tubes with Borda type and orifice type inlets were observed to be essentially the same, the effects of the orifice type inlets being slightly less pronounced (8, 9). Calculations and test data for the various tube geometries were in good agreement with the results of the three-step cylindrical seal (5).

The effects of conical-convergence on the mass flow rate and pressure signature were studied theoretically in (11) and experimentally in (12). The theoretical analysis demonstrated that the maximum stiffness occurs for an area ratio of 1.8. Experimentally, the results were not as dramatic, indicating moderate stiffness gains with an increased flow rate. The flow rates could be correlated using corresponding states methods along with an area ratio correction (12). The data and results reported from these various projects are rather complex to interpret. They represent extensive testing and two-phase-choked-flow calculations. Further, no direct comparisons between the seal data or recommendations for design purposes have been established.

Presented herein is a comparison of the leak rate and pressure signature data for three seal configurations, namely, (i) straight cylindrical, (ii) three-step cylindrical, and (iii) three-step labyrinth, in both the concentric and fully eccentric positions. Some recommendations are made, and applicability to other working fluids without the effects of rotation is noted. The seal configurations are illustrated, mass flow rates are directly compared; and a set of typical pressure profiles are discussed separately.

SYMBOLS

G	mass flow rate, $= \rho u$
G*	flow rate normalizing parameter, $= (P_c \rho_c / Z_c)^{1/2}$
P	pressure

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*A Borda inlet protrudes into the reservoir requiring a complete reversal (180°) of the flow streamline at the wall. An orifice type inlet is flush with the reservoir boundary requiring a 90° change in flow streamline at the wall.

**Jetting: the presence of a flat-monotone increasing diffuser type pressure profile over a portion of the tube usually near or below the saturation pressure based on inlet stagnation temperature for liquids and less pronounced and restricted close to the inlet for the gas.

T temperature

Z compressibility

ρ density

Subscripts

c thermodynamic critical

0 stagnation

r reduced, with respect to the thermodynamic critical value

GEOMETRIC CONFIGURATIONS

The basic flow facility was of the blowdown type (described in detail in (13)). The system was modified somewhat to accommodate the housing which simulated the seal configuration from the space shuttle main fuel pump interstage seal (1-3, 12). A cross section of the seal assembly is shown in Fig. 1. The conical adaptor flanges on each end were necessary to provide proper flow distribution and measurement of pressure and temperature. Photographs of the instrumented centerbodies simulating the rotor and housings of the three seal configurations are shown in Figs. 2 to 4.

Figure 2 shows the straight cylindrical seal which had seven pressure taps each at the 0 and 180° positions*, respectively, and one tap each at the 90° and 270° positions, 0.726 cm from the exit plane. The centerbody is 8.4244 cm in diameter by 4.13 cm long with a clearance of 0.0135 cm. The straight cylindrical seal is a simple concept but susceptible to manufacturing and operation tolerences as well as alinement problems. Such problems can be minimized by making the seal inlet conical-convergent and accepting the increased leak rates (12).

Figure 3 shows the three-step cylindrical seal, which had 11 pressure taps each at the 0 and 180° positions and one tap each at the 90° and 270° positions, 0.726 cm from the exit plane. In general, the clearence is 0.0127 cm with 0.038- to 0.051-cm slot spacing between shaft shoulder and the housing at each step and a total length of 4.62 cm. The shaft diameters were 7.9233, 7.8346, and 7.6944 cm, respectively, decreasing in the direction of flow. The three-step cylindrical seal is a relatively simple concept but is also subject to alinement, manufacturing, and operational tolerences as in the straight seal. Again, these problems can be reduced by making the seal steps conical-convergent.

Figure 4 shows two of the three step labyrinth seals with 12, 11, 10 teeth per step at nominal diameters of 8.077, 7.976, and 7.874 cm, respectively, in the direction of flow. The seals have 10 pressure taps at the 0 and 180° positions with an overall length of 4.38 cm. The three-step labyrinth seal is difficult to make, and its effectiveness can be readily reduced by manufacturing tolerences and/or one good rub.

The test fluids were nitrogen and hydrogen with a few tests run with gaseous helium as well.

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*Due to alinement problems, the minimum clearance was located approximately 15°±3° from the 0° position.

RESULTS AND DISCUSSION

The flow rates for the three seals possess many similarities, while the pressure profiles require a separate discussion for each configuration.

Flow Rates

While a great many theoretical calculations were made to relate the flow rates, the methods are complex, are described in (4) and (14-18), and will not be repeated herein.

The mass flow, leak rate, can be correlated in terms of a reduced mass flux

$$G_r = G/G^*$$

as a function of reduced inlet stagnation pressure

$$Pr_0 = P_0/P_c$$

with inlet stagnation temperature

$$Tr_0 = T_0/T_c$$

as a parameter. The G* is dependent only on the properties of the working fluid at the thermodynamic critical point. These corresponding states parameters have been used to correlate large sets of data for a variety of simple fluids (14-18). The mass flow results obtained with fluid nitrogen, as presented in this paper, indicate the applicability of these data to other fluids.

In figure 5(a) comparison of typical mass flow rates is made for liquid nitrogen at $Tr_0 = 0.67$ flowing through the straight cylindrical, three-step cylindrical, and three-step labyrinth seals, respectively. The flow through a venturi under similar conditions serves as a reference. The straight-cylindrical seal represents 0.6xGr-venturi (0.5xGr-venturi theory); the three-step cylindrical 0.35xGr-venturi; the three-step labyrinth, 0.26xGr-venturi.

On a relative basis, one can say that the straight seal behaves much like an orifice, the three-step seal provides approximately 1/3 less leakage, and the labyrinth seal provides the best leakage rate, about 1/2 that of the straight seal and 2/3 that of the three-step cylindrical seal. While the locii are for $Tr_0 = 0.67$, similar results are found for higher values of Tr_0 including ambient gas. Further, these results are not significantly influenced by eccentricity.

Pressure Profiles

Straight Cylindrical Seal: basically the profiles resemble those of pipe flow but there are some differences. In the concentric position the differences between the 0 and 180° profiles (within 15° of minimum and maximum clearance respectively, see sketches in Fig. 6) were small (1). For the fully eccentric position, the pressure differences are significant (Fig. 6). As the seal stiffness is directly related to this pressure difference, it is important to note the profile crossover region at approximately 80 percent of the seal length. It is anticipated that circumferential flow and separation causes the change. While the crossover region has only a small negative contribution to the total stiffness, it does render nearly 20 percent of the

seal length ineffective. For purposes of comparison, assign a relative stiffness value of unity to this seal. An absolute value is not required for this comparison.

Three Step Cylindrical Seal: In the concentric position, the steps serve as additional equivalent roughness in a pipe flow representation of the pressure profiles. In the fully eccentric position, the pressure differences are less than those noted for the straight cylindrical seal (cf., Figs. 6 and 7) in the first and second stages. But the appearance of a separation phenomenon, jetting, in the third stage represents a very significant pressure differential. The stiffness developed within this stage can be larger than for the other two stages combined. The phenomenon has been studied extensively in tubes (7-10) and to a lesser extent in multiple inlets (19-21). It appears primarly at low reduced inlet stagnation temperatures where $Tr_0 < 1$ with elevated inlet stagnation pres- sure. It is not markedly influenced by backpressure as high as $0.4P_0$. Without separation, the relative stiffness is less than for the straight cylindrical seal; however, with separation, the realtive stiffness becomes much larger. Control of such separation effects are important; too much stiffness can be as detrimental as none at all.

Three Step Labyrinth Seal: A typical labyrinth tooth is sketched in Fig. 8. To the flow, such teeth probably represent a series of sequential inlets, or, more crudely, a very rough passage. However, as one might expect, the most effective teeth are at the inlet and near the exit. It may further be noted that both the centered and fully eccentric profiles are similar. The differences being that, in the eccentric position, there is a significant pressure drop at the inlet followed by a similar rise at the exit which characterizes each stage. These results can be explained in terms of circumferential flows. More noteworthy is that the integrated pressure differences are nearly zero, indicating little or no stiffness for such a seal. In some instances, stiffness and dampening have increased by blocking the circumferential flow and vortex formation using longitudinal ribbing (3). No testing was done in this work to determine the effect of ribbing.

So to summarize the pressure profile characteristics, the straight cylindrical seal has moderate to good stiffness characteristics, the three-step cylindrical has moderate to high stiffness with fluid jetting, and the three-step labyrinth little or no stiffness. Longitudinal ribbing can increase stiffness.

SUMMARY OF RESULTS

Three seal configurations applicable to high performance turbomachines have been evaluated and the following advantages, limitations, and recommendations are noted:

1. For the straight cylindrical seal, one can expect
   - Moderate to good leakage control
   - Moderate to good stiffness (ability to restore a perturbed shaft)
   - Simple concept.

This seal's limitations are that it is subject to tolerance problems arising from manufacturing, pressure, temperature, and alinement sensitivities, and has a large area for energy dissipation and thus the potential of catastropic rubs.

When such seals are used, it is recommended that they be conical-convergent to enhance stiffness, minimize the tolerance problems, and make acceptable a slightly higher leak rate.

2. For the three-step cylindrical seal, one can expect

Moderate leak rate control

Moderate to high stiffness with fluid jetting (Fluid jetting can occur through the third stage, is prevalent at reduced temperatures less than one, and can occur even when the reduced backpressure is greater.)

Relatively simple concept

This seal's limitation is that it is subject to the same tolerance problems as the straight cylindrical seal.

The three-step cylindrical seal can be recommended for flow and dynamic control. See also recommendations for inlet convergence cited previously.

3. For the three-step labyrinth seal, one can expect

Very good leak rate control

Very poor stiffness - depending on labyrinth cavity design.

If the cavity approaches the straight clyindrical design, then leakage rates increase, stiffness increases, and the circumferential flow decreases; the limiting performance is the same as that of the straight cylindrical seal. If the cavity approaches the geometry of a series of sequential orifices, the leakage rate decreases, the circumferential flow increases, and the net stiffness will be essentially zero.

This seal's limitations are that it is a complex geometry with associated manfacturing tolerence problems, etc.; it has little energy dissipation for a rub; and a hard rub can virtually destroy its excellant leakage characteristics.

This seal is recommended for leak rate control but not recommended for dynamic control without longitudinal ribbing to control circumferential flow and vortex formation.

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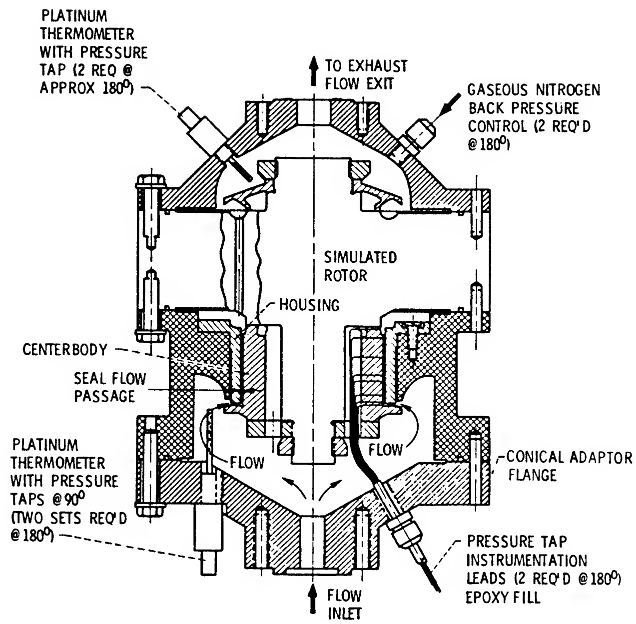

Figure 1. - Cross-section view of simulated seal configuration.

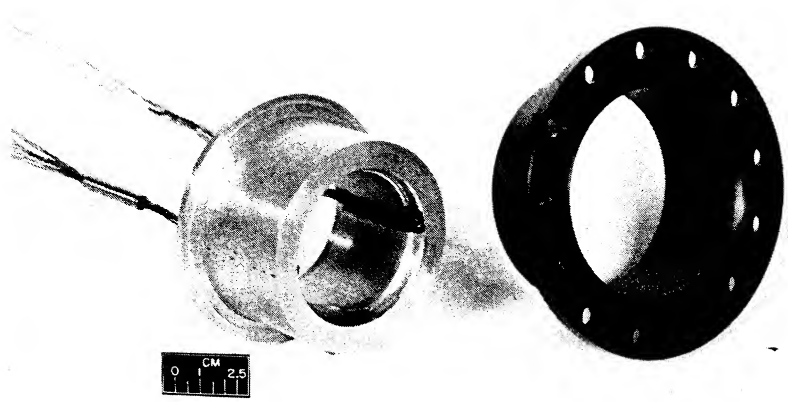

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Figure 2. - Straight-cylindrical seal.

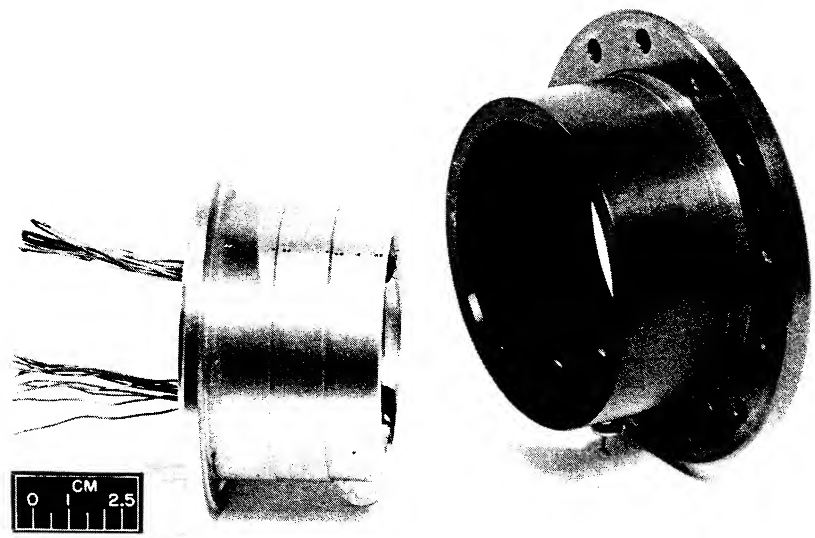

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Figure 3. - Three-step-cylindrical seal.

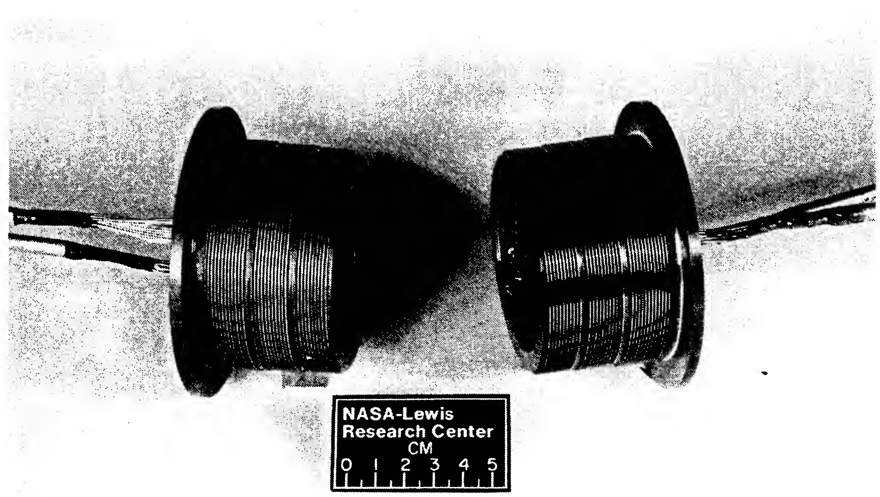

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Figure 4. - Three-step labyrinth seal.

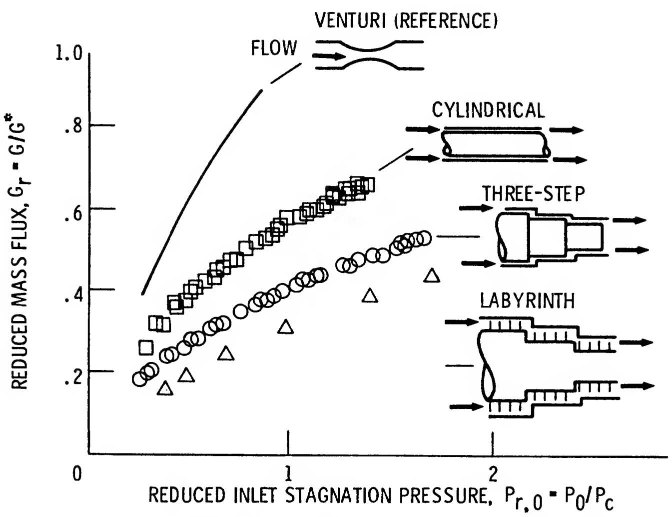

Figure 5. - Reduced mass flow or leak rate as function of reduced inlet stagnation pressure for three seal configurations. Test fluid, liquid nitrogen; $T_{r,0} = 0.67$.

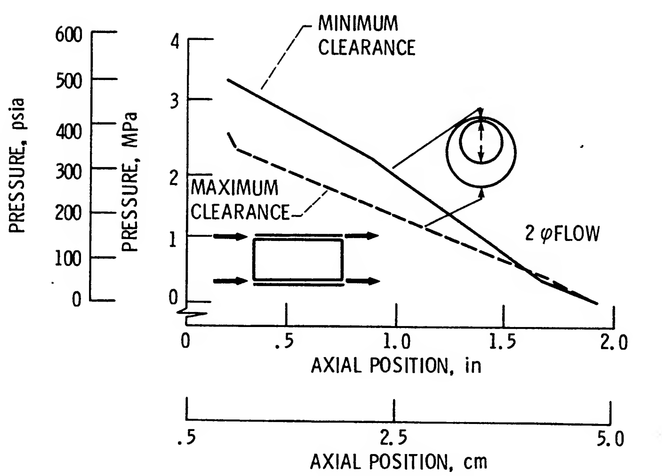

Figure 6. - Axial pressure profiles for the straight cylindrical seal in its fully eccentric position. Test fluid, liquid nitrogen, $T_{r,0} = 0.67$.

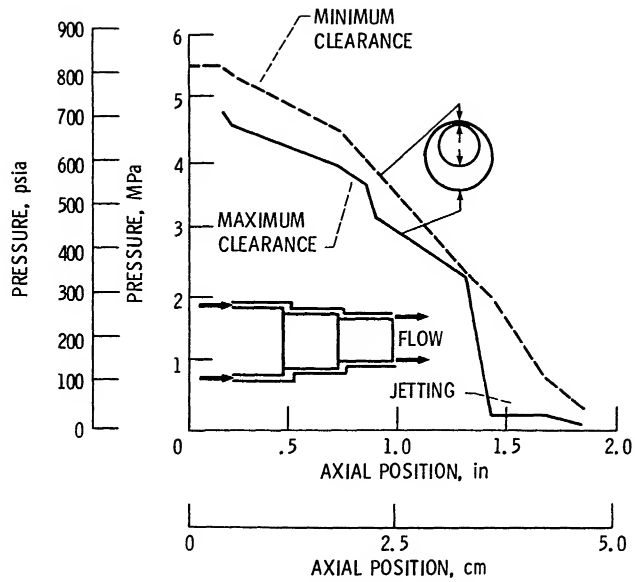

Figure 7. - Axial pressure profiles for the three step cylindrical seal in its fully eccentric position. Test fluid, liquid nitrogen; $T_{r,0} = 0.67$.

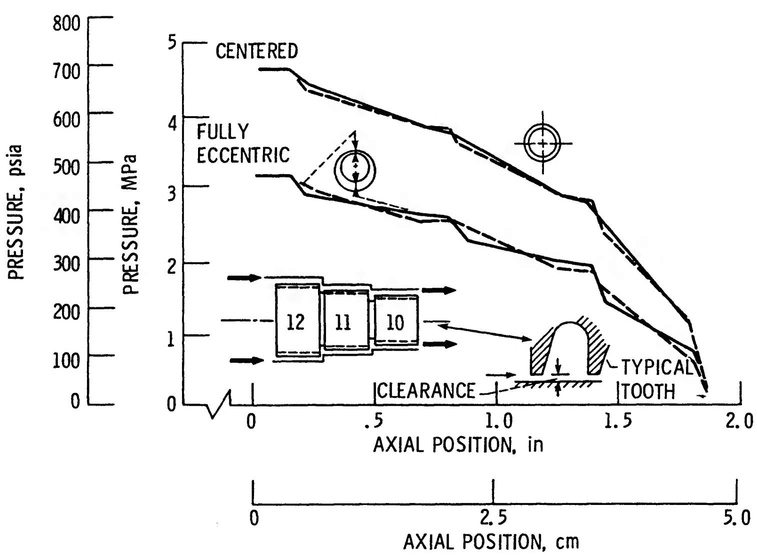

Figure 8. - Axial pressure profiles for the three-step labyrinth seal in its concentric and fully eccentric positions. Test fluid, gaseous nitrogen.

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16. Abstract

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